

Electrical Protection of Cellular Radio Sites

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Significance:

Part 6 – Textbooks, tutorials, and reviews

This invited lecture was presented at the Extension Division of the University of Wisconsin at a time when cellular telephone (hence the somewhat obsolete wording of the title) had not yet reached its wide acceptance, but system designers were rightfully concerned with surge protection of that emerging technology. One particular aspect of a cell phone relay tower is that it is often installed on hilltops where securing low-impedance earthing electrodes can be difficult.

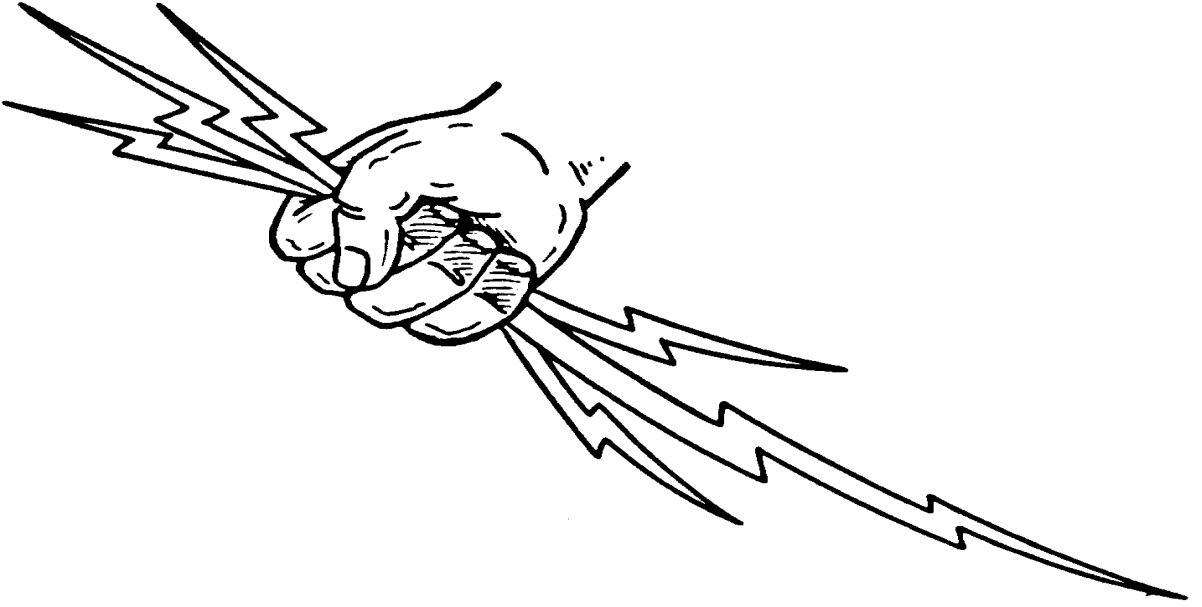
The text handed out paralleled a slide presentation – not included in this reprint – calling attention to the three ports where surges could impact operation and, at worst, integrity of a “cellular radio site” (hand-held units were not included):

- connection to the power supply system
- connection to landline network(s)
- tower antenna acting as lightning air terminal

With now 20 years of experience in operation and protection of cell phone facilities, the protective techniques might have evolved, but the concerns remain valid.

Cellular Radio II

ELECTRICAL PROTECTION



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ELECTRICAL PROTECTION OF CELLULAR RADIO SITES

INTRODUCTION

Hardware installed at a cellular radio site will be exposed to transient overvoltages which can upset the data processing or, worse, cause permanent damage of sensitive electronic components.

The hazards associated with lightning or power system switching transient overvoltages (surges) have existed ever since electronic equipment began to displace the older electro-mechanical devices. Therefore, these hazards are not a new threat to the successful operation of cellular radio systems; rather, the combination of three ports connected to the hardware presents some new problems, but they can be solved by proper application of known techniques and devices. The connection to the power supply, the connection to the telephone cable plant, and the exposure of the antenna to lightning strikes are three ports through which upsetting or damaging transient overvoltages can impinge on the hardware. While a click in a telephone conversation would not be objectionable, an upset of digital commands might be. Permanent damage, of course, should be avoided as much as possible.

This presentation will give an overview of the nature of the surges likely to enter by each of the three ports. A brief review will then be given of the techniques and devices available for diverting or attenuating these surges. The effectiveness of these techniques and devices has been demonstrated in other existing electronic systems; therefore, reliable protection of cellular radio hardware can also be expected under most operating conditions.

IMPINGING SURGES

Power Supply System

The power supply system for a site will be whatever the local electric utility supplies to its customers. Studies and standards have been published, describing the nature of the surges that can be expected to occur on such a power supply.⁽¹⁻³⁾

Fortunately for the reliability of the cellular radio equipment, the actual power supply to the electronics is a dc source, needed to assure continuity of service in case of failure of the utility system. This supply takes the form of a dc battery with a charger powered by the utility grid. Provided that the charger can withstand the impinging surges from the utility supply, the battery will act as a very effective buffer for the disturbances, including surges, occurring in the utility grid.

The existence of power supply surges has been recognized in the telephone industry, and FCC regulations (Part 68) do provide a standard for withstand capability of the ac input of electronics interfacing the power supply and the cable plant. Therefore, cellular radio hardware will be required to meet the same requirements as all other peripherals now being used at subscribers facilities. The FCC standard is a voltage impulse of 2500 V peak with a duration of 10 μ s and a short-circuit current of 1000 A.⁽⁴⁾ It is a severe test, but equipment designed to withstand that impulse has been found to have satisfactory survival capability in service, which is the ultimate proof that the standard is appropriate.

Cable Plant

The wire connection of the cell hardware to the telephone system will present the same characteristics as a conventional connection to a multi-line subscriber. The telephone industry has a long and successful experience in dealing with surges that can appear on the wire pairs. Of course, there has been a downward trend in the withstand capability of terminal equipment as old electromechanical equipment has been superseded by modern solid-state equipment. Fortunately, concurrent advances in protective devices have enabled system operators to maintain reliability of these more sensitive components. A wide range of protective devices is available, meeting requirements designed specifically for this type of service.⁽⁵⁻⁸⁾

Antenna Feed

The very nature of an antenna, especially a top-mounted omni-directional antenna, makes it a very good lightning rod. Thus, there is a definite likelihood that a lightning bolt will, from time to time, terminate on an antenna. It is possible to provide some protection — mostly by diverting the lightning current to earth — but some damage to the antenna by the current burning effect, or to the electronics by the overvoltage, is still likely to occur. The probability of a tower being hit by a lightning bolt can be estimated with reasonable accuracy for the general case, but not with good precision for any particular site. Equations, which are based on actual experience, relate the number of strikes terminating on a tall object to its height and geographical location.⁽⁹⁻¹¹⁾ A recent study has been published, assessing the lightning damage threat in the United States,⁽¹²⁾ which provides a better picture of the situation than the traditional "isokeraunic map" based on the number of days where thunder is heard.

Ground Potential Differential

The three sources of surges discussed above have all been taken one at a time, with the implication that they might carry a surge voltage within themselves. This type of surge is the so-called "normal mode," or "transverse mode." In site hardware, the power supply and the antenna feed conductors include a connection to ground, while the telephone connection will be a balanced pair. There is another way for surges to appear, the so-called "common mode" where, for instance, two pairs of telephone cable are simultaneously elevated in potential above ground. However, as the telephone terminal equipment is connected across the pair, the amplifiers inputs are not stressed between terminals, but the insulation with respect to ground will be stressed.

Each of the three ports at the cell can bring a surge with respect to the ground, and therefore produce different potentials with respect to ground, unless adequate common grounding is applied. It is a dangerous fallacy to proclaim that electrical noise can be avoided by using separate grounds.

FUNDAMENTAL PROTECTION TECHNIQUES

Protection of a power system, of a communication system, or of an electronic black box against the threats of the surge environment can be accomplished in different ways. There is no single truth or magic cure ensuring immunity and success, but, rather, there are a number of valid approaches that can be combined as necessary to achieve the goal. The competent protection engineer can contribute his knowledge and perception to the choice of approaches against a threat which is imprecise and unpredictable, keeping in mind the need to balance the technical goal of maximum protection and the economic goal of realistic protection at an acceptable cost. However, just as in the case of accident insurance, the cost of the premium appears high before the accident, not after.

A discussion of fundamental protection techniques that is limited in time and scope has the risk of becoming an inventory of a bag of tricks; yet, there are some fundamental principles and fundamental techniques that can be useful in obtaining transient immunity, especially at the design stages of an electronic system or circuit. All too often, the need for protection becomes apparent at a late stage, when it is much more difficult to apply the fundamental techniques which are most effective and economical when implemented at the outset.

Protection techniques can be classified into several categories according to the purpose and the system level at which the engineer is working. For the system as a whole, protection is primarily a preventive effort. One must consider the physical exposure to transients – in particular, the indirect effects of lightning resulting from building design, location, physical spread, and coupling to other disturbance sources – as well as such inherent susceptibility characteristics as frequency response and nominal voltage.

For many system components or electronic black boxes, the environment is often beyond the control of the designer or user, and protection becomes a curative effort – learning to live and survive in an environment which is imposed. Quite often this effort is motivated by field failures, so that retrofit is needed. The techniques involved here tend to be the application of protective devices to circuits or a search for inherent immunity rather than the elimination of surges at their origin. However, in the case of cellular radio hardware, the opportunity exists to integrate all protective measures at the outset of the design and thus optimize the protection.

Another distinction can be made in classifying protective techniques. Granted that surges will be unavoidable, one can attempt to block them, divert them, or strive to withstand them; the latter, however, is generally difficult to achieve alone.

SHIELDING, BONDING, AND GROUNDING

Shielding, bonding, and grounding are three interrelated methods for protecting a circuit from external transients. Shielding consists in enclosing the circuit wiring in a conductive enclosure, which in theory cancels out any electromagnetic field inside the enclosure; actually, it is more an attenuation than a cancellation. Bonding is the practice of providing low-impedance connections between adjacent metal parts, such as the panels of a shield, cabinets in an electronic rack, or rebars in a concrete structure. Grounding is the practice of providing a low impedance to "earth," through various methods of driving conductors into the soil. Each of these techniques has its limitations, and each can sometimes be overemphasized.

Shielding

Shielding conductors by wrapping them in a "grounded" sheath or shielding an electronic circuit by enclosing it in a "grounded" conductive box is a defensive measure that occurs very naturally to the system designer or laboratory experimenter anticipating a hostile electromagnetic environment. Difficulties do arise, however, when the concept of "grounded" is examined in detail and when the objectives of shielding for noise immunity conflict with the objectives of shielding for lightning surge immunity.

A shield can be the size of a matchbox or a building; it can cover a few inches of wire, or kilometers of buried or overhead cables. "Grounding" these diverse shields is not an easy thing to do because the impedance to earth of the grounding connection must be acknowledged. The situation is made even more controversial because of the conflict between the often-proclaimed design rule "ground cable shields at one end only," a rule justified by noise immunity performance, in particular common mode noise reduction – and the harsh reality of current flow and Ohm's law when lightning strikes.

This conflict is actually very simple to resolve if recognized in time: provide an outer shield, grounded at both ends (and at any possible intermediate points); inside this shield the electronic designer is then free to enforce his

single-point grounding rules. In this approach, the only drawback is the hardware cost of "double shields." However, in many installations there is a metallic conduit through which the cables are pulled; with simple but close attention to maintaining the continuity of this conduit path, through all the joints and junction boxes, a very effective outer shield is obtained at negligible additional cost. In the case of underground conduit runs, the most frequent practice is to use plastic conduit, which unfortunately breaks the continuity. System designers would be well advised to require metal conduits where the circuits are sensitive or, at a minimum to pull a shielded cable in the plastic conduit where the shield is used to maintain continuity between the above-ground metal conduits. That additional cost, then, is the insurance premium, which is well worth accepting.

Bonding

We have already mentioned one aspect of bonding in describing the need for continuity of the outer shield. Another instance of bonding occurs where the shield of an incoming cable is connected to the box of the circuit or to the building ground. The principle is simple: the shield can be viewed as an extension of the box, and thus bonding of the shield to the box should be continuous over 360°. In practice, unless special connectors are used, this is difficult to achieve, for often a shielded cable is terminated at a connection board with the shield peeled back and turned into a pigtail, which in turn is connected to the "ground" terminal of the connection board. One can imagine the many possible variations of current flow, with the shield current now flowing in the pigtail and the creation of the corresponding electromagnetic radiation at the point of cable entry.

Adjacent cabinets in a lineup must be bonded together for safety as well as transient and noise immunity. In principle, a flat strap has a lower inductance than a round wire of the same area. Actually several strategically located smaller wires provide a much more effective bond than one massive strap either round or flat. The difficulty lies in implementing this alternate view, and overcoming the comforting sight of a large grounding strap at the bottom of the cabinet lineup. Such a strap does no harm and is a good safety practice, but it may not do as much good as expected from the point of view of surge protection.

Grounding

Grounding, which is also referred to as "earthing," has different meanings as well as different roles. The primary definition is the connection of the circuit, shield, or reference to "earth." But what is "earth"? System designers, construction crews, inspectors, and technical conference authors are concerned with establishing, measuring, and maintaining a low ground "resistance," often determined by dc measurements on rods driven into the ground. Driving rods into the ground does not ensure a low impedance under the transient conditions of high rate of current change associated with lightning discharges. This remark is not intended as a criticism of the efforts going into achieving a low resistance

but, rather, to alert the system designer that there is more to it than just low resistance, and that one can overdo the act of burying copper in the ground.⁽¹³⁻¹⁵⁾

When one deals with a reasonably compact system, be it cabinet-size, room-size, or building-size, it is more effective to view the grounding as a well-bonded connection to the outer shield (if any), building frame, or cabinet enclosure. The resistance (impedance) from that reference to "earth" is not very significant as long as other wires at "ground" potential are not brought to the system. This desirable situation is best obtained with single-point grounding approaches, as opposed to multiple grounding. There is a controversy over the respective advantages and disadvantages of the two approaches for general cases, but examination of the characteristics of specific cases will resolve the controversy. Since there is little chance of dealing with an absolutely isolated system, the question is: What should be done with incoming wires? These wires can be isolated from the local ground during normal operation, but one must recognize that, during transient conditions of lightning surge or power system faults, high voltages will appear across these isolated wires and local ground, voltages which, in some cases, are totally beyond the withstand capability of insulation. That insulation, then, must be protected by suitable devices which in fact do connect the wires to the local ground for the duration of the transient. This type of grounding is one function of transient suppressors.

It is a dangerous illusion to believe that lightning effects can be eliminated by the isolation of conductors or subsystems. It is much safer and quite acceptable, if included in the design, to provide bonding during transient conditions by suitable protective devices. The important point to remember is that while lightning is a fairly well-defined phenomenon, with known characteristics and effects in general, its probability of occurrence at a particular location is unknown. For the successful operation of a system, foresight is needed in applying fundamental protection techniques at the beginning.

PROTECTIVE DEVICES

Various devices have been developed for protecting electrical and electronic equipment against transients. They are often called "transient suppressors" although, for accuracy, they should be called "transient limiters," "clamps," or "diverters" because they cannot really suppress transients; rather, they limit transients to acceptable levels or make them harmless by diverting them to ground.

There are two categories of transient suppressors: those that block transients, preventing their propagation toward sensitive circuits, and those that divert transients, limiting residual voltages. Since many of the transients originate from a current source, the blocking of a transient may not always be possible; the diverting of the transient is more likely to find general application. A combination of diverting and blocking can be a very effective approach. This approach generally takes the form of a multistage circuit,

where a first device diverts the transient toward ground, a second device – impedance or resistance – offers a restricted path to the transient propagation but an acceptable path to the signal or power, and a third device clamps the residual transient. Thus, we are primarily interested in the diverting devices. These diverting devices can be of two kinds: short-circuiting devices (crow-bar) or voltage-clamping devices.

Because the technical and trade literature contains many articles on these devices, we shall limit the discussion of the details and refer the reader to References 16-29. We shall, however, make some comparisons to point out the significant differences in performance.

Crowbar Devices

The principle of crowbar devices is quite simple: upon occurrence of an overvoltage, the device changes from a high-impedance state to a low-impedance state, offering a low-impedance path to divert the surge to ground. Spark gaps, including gas tubes and carbon blocks extensively used in the telephone industry, are examples of crowbar devices.

The major advantage of the crowbar device is that its low impedance allows the flow of substantial surge currents without the development of high energy within the device itself; the energy has to be spent elsewhere in the circuit. This "reflexion" of the impinging surge can also be a disadvantage in some circuits when the transient disturbance associated with the gap firing is being considered. Where there is no problem of power-follow (discussed below), such as in some communication circuits, the spark gap has the advantage of very simple construction with potentially low cost.

The crowbar device, however, has three major limitations. One is the volt-time sensitivity of the breakdown process. As the voltage increases across a spark gap, significant conduction of current – and hence the voltage limitation of a surge – cannot take place until the transition occurs to the arc mode of conduction, by avalanche breakdown of the gas between the electrodes. The load is left unprotected during the initial rise because of this delay time (typically in microseconds). Considerable variation exists in the spark-over voltage achieved in successive operations, since the process is statistical in nature. This sparkover voltage, in addition, can be substantially higher after a long period of rest than after successive discharges.

The second limitation is associated with the sharpness of the sparkover, which produces fast current rises in the circuits and, thus, objectionable noise. An effect of this fast current change can be found in some hybrid protective systems. The gap does a very nice job of discharging the impinging high-energy surges, but the magnetic field associated with the high rate of current change (di/dt) induces a voltage in the loop adjacent to the secondary suppressor, adding what can be a substantial spike to the expected secondary clamping voltage.

A third limitation occurs when a power current from the steady-state voltage source follows the surge discharge (follow-current, or power-follow). In ac circuits, this power-follow current may or may not be cleared at a natural current zero. Additional means, therefore, must be provided to open the power circuit if the crowbar device is not designed to provide self-clearing action within the specified limits of surge energy, system voltage, and power-follow current. This combination of a gap with a current-limiting, nonlinear varistor has been very successful in the utility industry as a surge arrester or surge diverter.

Voltage-clamping Devices

Voltage-clamping devices have variable impedance, depending on the current flowing through the device or the voltage across its terminal. These components show a nonlinear characteristic – that is, Ohm's law can be applied, but the equation has a variable. Impedance variation does not contain discontinuities, in contrast to the crowbar device, which shows a turn-on action. As far as their volt-ampere characteristics are concerned, these components are time-dependent to a certain degree. However, unlike the spark-over of a gap or the triggering of a thyristor, time delay is not involved.

When a voltage-clamping device is installed, the circuit remains essentially unaffected by the device before and after the transient for any steady-state voltage below clamping level. Increased current drawn through the device as the surge voltage attempts to rise results in voltage-clamping action.

The principle of voltage clamping can be achieved with any device exhibiting this nonlinear impedance. Two categories of devices, having the same effect but operating on very different physical processes, have found acceptance in the industry: the polycrystalline varistors and the single-junction avalanche diodes. Another technology, the old selenium rectifier, has been practically eliminated from the field because of the improved characteristics of modern varistors.

Avalanche diodes, the Zener diodes, were initially applied as voltage clamps, a natural outgrowth of their application as voltage regulators. Improved construction, specifically aimed at surge absorption, has made these diodes very effective suppressors. Large-diameter junctions and low thermal impedance connections are used to deal with the inherent problem of dissipating the heat of the surge in a very thin single-layer junction.^(26,27)

The advantage of the avalanche diode, generally a P-N silicon junction, is the possibility of achieving low clamping voltage and a nearly flat volt-ampere characteristic over its useful power range. Therefore, these diodes are widely used in low-voltage electronic circuits for the protection of 5 or 15 V logic circuits, for instance. For higher voltages, the heat generation problem associated with single junctions can be overcome by stacking a number of lower voltage junctions, admittedly at some extra cost.

The term *varistor* is derived from its role as a *variable resistor*. It is also called a *voltage-dependent resistor*, but that description tends to imply that the voltage is the independent parameter in surge protection, which is not correct. Two very different devices have been successfully developed as varistors: silicon carbide disks have been used for years in the surge arrester industry, and, more recently, metal oxide varistor technology has come of age.⁽²⁸⁾

In silicon carbide varistors, the physical process of non-linear conduction is not completely understood, and the manufacturing of the material, successful as it is, has remained an art. It appears that the process takes place at the tips of the grains of silicon carbide which are held together by a binder. The story goes that the device action was found accidentally by having a grinding wheel, on a disorderly work bench, accidentally connected to an experimental circuit; for many years silicon carbide varistors indeed looked like grinding wheels, each complete with a hole in the center.

Metal oxide varistors depend on the conduction process occurring at the boundaries between the large grains of oxide (typically zinc oxide) grown in a carefully controlled sintering process. The physics of the nonlinear conduction mechanism have been described in the literature.⁽²²⁻²⁴⁾

COMPARISONS OF PROTECTIVE DEVICES

Spark Gap Versus Varistor

The choice between these two devices will be influenced by the inherent characteristics of the application. Where power-follow is a problem, there is little opportunity to apply a simple gap. The operation of a gap on a power system can cause sags in the voltage when the crowbar action persists until the next current zero; varistors do not cause these sags. Where very steep front transients occur, the gap alone may let an excessive voltage go toward the "protected" circuit until the voltage is limited by sparkover. Where the capacitance of a varistor is objectionable, the low inherent capacitance of a gap seems attractive. If very high energy levels (compared to the lower levels inherent with the crowbar action of a gap) are likely to be deposited in a varistor by an impinging surge, then a high capacity surge arrester near the service entrance may be combined with a lower clamping voltage varistor installed farther into the circuit. This combined protection, however, requires adequate coordination between the two suppressors.⁽³⁰⁾

Avalanche Diode Versus Varistor

The basic performance characteristics of these two devices are similar, and therefore the choice may be dictated by clamping voltage requirements (the avalanche diode is available at lower clamping voltages), by energy-handling capabilities (the varistor is generally higher in capability per unit of cost), and by packaging requirements (the varistor material is more flexible and does not require hermetic packaging).

Failure Modes

Failure of an electrical component can occur because its capability was exceeded by the applied stress or because some latent defect in the component went by unnoticed in the quality control processes. While this situation is well recognized for ordinary components, a surge protective device, which is no exception to these limitations, tends to be expected to perform miracles, or at least to fail gracefully in a "fail-safe" mode. The term "fail-safe," however, may mean different failure modes to different users and, therefore, should not be used. To some users, fail-safe means that the protected *hardware* must never be exposed to an overvoltage, so that failure of the protective device must be in the fail-short mode, even if it puts the system out of operation. To other users, fail-safe means that the *function* must be maintained, even if the hardware is left temporarily unprotected, so that failure of the protective device must be in the open-circuit mode. It is more accurate and less misleading to describe failure modes as "fail-short" or "fail-open," as the case may be.

SPECIFIC APPLICATIONS

Trial systems of cellular radar (AMPS and ARTS) as well as conventional mobile radio base stations provide a basis for field experience in the techniques of protection. The practices or recommendations described in this section reflect the combined experience of three organizations involved in this technology: Bell Laboratories, Mobile Radio Department of General Electric, and Motorola Communications and Electronics.

Actual damage experience has been limited to one outage after a major lightning strike, but a single module replacement by field personnel restored the normal operation. Automatic monitoring of the antenna performance has been sufficient to detect minor antenna damage due to lightning; this type of degradation can then be corrected by routine maintenance.

This success story is the result of thorough application of the principles discussed earlier. Inspection of a cell site reveals a grounding scheme that includes extensive grounding rods and well-bonded rings (called "halo" when installed at the top of the inside wall of the building, in contrast to floor-level rings). Systematic bonding of conduits, cabinets, and enclosures is mandatory.

At a typical site, the power line protection starts at the utility distribution transformer with a primary surge arrester. The meter socket and service antenna panel are grounded to the local unit. Surge arresters are provided on the load side of the service panel, protecting the rectifiers for the dc supply to the 24 V storage batteries. The limited 120 V ac loads (test instruments and fans) are supplied by an inverter fed from the battery.

The cable input from the wireline plant is first protected at the point of entry by conventional protectors. While in

some installations this has been the only protection, further protection is recommended by the use of three-electrode gas tubes, as a prudent and ultimately cost-effective backup protection.

The major threat associated with lightning has been successfully overcome by extensive grounding and shielding. The tubular post construction for the antenna, rather than the lattice tower, offers a very effective method of shielding the antenna feed line. Lightning current flows on the outer shell of the post, leaving the coax cables unharmed inside. The extent of the outside grounding network (rods vs. mats or radials) can be determined by prudent practice, guided by cost-weighting factors involving the past history and practices of the general site area, and the water table condition of the site on a year-round basis. Both power companies and local telephone companies generally have well-developed experience in this area.

Field experience has shown that problems arose when the antenna elements were not bonded to the overall ground ("dc ground" as opposed to "RF ground") system. This bonding is done at the tower top, at intermediate tie points, and, most important, at the base of the tower and hatch plate entrance to the building. Some of the relatively small details in grounding practices, which can be described as 2% increments in protection costs, have been found to yield a 50% improvement in lightning withstand capability.

When the precautions have been applied, operators and manufacturers express confidence in the reliability. While none would be foolhardy to claim immunity, all have found that an effective protection can be achieved.

Systematic application of protective techniques, including shielding, bonding, and grounding will allow diversion of lightning currents directly to earth, with a minimum amount of residual stress for the electronics. The residual stress can then be dealt with by suitable surge protective devices.

CONCLUSIONS

Electrical protection of cellular radio sites can be obtained by appropriate application of protective techniques and protective devices. The effectiveness of these has been demonstrated in trial systems of cellular radio as well as in their long-successful application in power systems, telephone wireline systems, and conventional mobile radio systems.

Surge protective devices are available for protecting low-voltage electronics. Two basic types offer different characteristics: crowbar devices have high-current capability but generally involve power-follow when applied on a power system; voltage clamping devices, either silicon avalanche or varistors, are free from the power-follow problem.

Avalanche diodes offer low clamping voltage, which makes them most suitable for low-voltage, low-power electronics. Metal oxide varistors are now available in a wide range of clamping voltages and energy-handling capacities. Spark gaps, while having some limitations, are widely used

on telephone circuits, mostly in the form of gas tubes. Each of these devices has its own best field of application, insuring greater reliability of the circuits in the electromagnetic environment of power and communication systems.

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FOR FURTHER READING

Lightning

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